This document was too large to scan as a single document. It has been divided into smaller sections.

Section 5 of 5

Document Information			
Document #	HW-18700		
Title	REDOX TECHNICAL MANUAL		
Date	07/10/1951		
Originator	WOODFIELD FW	Originator Co.	GE, HAPO
Recipient		Recipient Co.	
Keywords	MANUALS, NUCLEAR MATERIALS CONTROL & ACCOUNTABILITY, SEPARATION PROCESSES & PROCEDURES, WASTE TREATMENT & DISPOSAL		
Project	REDOX, DECLASS		
Inspected Date	07/13/2005		

8. Other Process Chemicals

Other process chemicals, such as sodium nitrate, are not hazardous enough to warrant a detailed discussion. Reasonable care should be exercised, however, in handling them to avoid skin contact and to insure that ingestion does not occur.

1942

[redacted] 2416 DECLASSIFIED HW-1[redacted]

REFERENCES

(1) Beatty, Berger, and Shronk, Determination of the Oxides of Nitrogen by the Phenoldisulfonic Acid Method, U. S. Bureau of Mines R. I. 3687, (1943).

(2) Brandt, Industrial Health Engineering, John Wiley and Sons, Pp. 5-8, (1947).

(3) Brookes and Alyea, Poisons, D. Van Nostrand, Pp. 37, 94-95, (1946).

(4) Elkins, Chemistry of Industrial Toxicology, John Wiley and Sons, Pp. 69, 84, 118-119, 224, (1950).

(5) Hamilton and Hardy, Industrial Toxicology, Paul B. Hoeber, P. 29, (1949).

(6) Henderson and Haggard, Noxious Gases, Rheinhold Publishing Corporation, P. 137, (1943).

(7) Huff, Annual Report of the Explosives Division, U. S. Bureau of Mines R. E. 3537, Pp. 2, 11, 13, (1940).

(8) Jacobs, Analytical Chemistry of Industrial Poisons, Hazards, and Solvents, Interscience Publishers, Pp. 280, 541, (1941).

(9) Moulton, National Fire Codes, Vol. I, National Fire Protection Association, Pp. 519, 534, (1948).

(9a) Patty, Industrial Hygiene and Toxicology, Vol. II, Interscience Publishers, Inc., P. 610, (1949).

(10) Methyl Isobutyl Ketone, Shell Chemical Corporation, Pp. 66-67, (1948).

(11) GE-H-13235 1200 Area Pilot Plant Manual of Operations. D. G. Reid and N. J. Rigstad. Pp. 822-826. 9-1-47.

(12) KAPL-250 Limits of Inflammability and Ignition Temperatures of Hexone in Air and in Other Gaseous Atmospheres. H. W. Alter. 9-9-49.

[redacted] [redacted]

PART V: SAFETY, continued

CHAPTER XXV. CRITICAL MASS CONTROL

CONTENTS

CHAPTER XXV. CRITICAL MASS CONTROL

A. INTRODUCTION

The main plutonium isotope, Pu^{239}, and the uranium isotope U^{235}, are both capable of self-sustained fission reactions. Although both of these nuclides are handled in the Redox process, a U^{235} chain reaction is impossible under the conditions of the Redox process. The U^{235} is present only in association with neutron-absorbing U^{238} (as in the natural uranium charged to the piles). This chapter, therefore, deals only with Pu^{239} critical mass control.

Pu^{239} is capable of both slow-neutron and fast-neutron chain reactions. Slow-neutron chain reactions result when the neutrons released by the fission of a Pu^{239} nucleus are moderated to low energy levels by collisions with other kinds of atoms before capture by other Pu^{239} nuclei, which in turn fission and continue the reaction. Fast-neutron chain reactions are basically the same, except that the free neutrons undergo no moderation and thus lose no energy before capture. A certain quantity of plutonium must be present before a chain reaction can take place. This quantity is called the critical mass. The fission capture cross-section for plutonium is smaller for fast-neutrons than for slow-neutrons. Thus the critical mass for a fast-neutron reaction is larger than for a slow-neutron reaction — not less than 5 kilograms for a fast-neutron reaction as compared to a minimum of approximately 0.6 kilogram for a water-moderated slow-neutron reaction. Fast-neutron reactions can take place only at high plutonium concentrations (above about 5000 g./l.) and atomic ratios of hydrogen to plutonium below 5, and are thus impossible under the conditions of the Redox process.

This chapter is concerned only with the technical and experimental background of the plutonium critical mass for slow-neutron reactions and the safeguards necessary to prevent a critical accumulation. It will be evident from the following sections that critical mass control is of concern only in connection with those process vessels which contain the plutonium after it has been separated from uranium in the IB Column.

B. CRITICAL MASS FOR SLOW-NEUTRON FISSION

This section is concerned only with the size of the critical mass for slow-neutron fission, as this type of criticality is the only one of importance to the Redox process. The amount of plutonium required to reach criticality is dependent upon the relative abundance of the various plutonium isotopes, the concentrations of plutonium and other chemical elements in the assembly, the geometry of the assembly, and the nature of the materials surrounding it. At the time of this writing the Pile Technology Division of the Hanford Works is in the process of determining the critical masses for water-moderated slow-neutron chain reactions in stainless-steel spheres and cylinders. The following subsections list some preliminary results of these experiments and some conclusions that

have been reached as a result of these and other critical mass studies.

1. Minimum Critical Mass

The lowest conceivable critical mass of plutonium under any conditions that may be anticipated in the Redox Plant occurs when the plutonium is uniformly distributed in a sphere of an optimum diameter (12 to 15 inches) moderated and surrounded by water. Values for the critical mass under these conditions will be referred to as the "minimum critical mass". The value of the minimum critical mass varies slightly with the total pile exposure that the parent slugs receive, because of the formation of greater relative amounts of Pu^{240} with increased pile exposure. Pu^{240} has a poisoning effect and acts to inhibit Pu^{239} criticality. It is not possible to determine the minimum critical mass directly, as the plutonium solutions must contain sufficient acid concentrations to prevent plutonium precipitation and must be handled in vessels whose construction material will have some effect on the critical mass. The actual minimum critical masses are therefore determined by applying appropriate corrections (for the effects of foreign ions and of the vessel walls) to the directly observed values. The minimum critical mass for plutonium produced in slugs with a total pile exposure of 420 megawatt-days per ton is shown on Figures XXV-1 and XXV-2. Minimum critical mass values for several exposure levels are as follows:

Total Exposure Received By Parent Slugs, Megawatt-Days/Short Ton of U	Corresponding Plutonium Concentration, G. Pu/Ton U	Minimum Critical Mass, G. Pu
212	195	533
420	380	595
605	530	613

The 420 Mw.-day critical mass value is believed to be accurate within ±3 per cent, while the others are conservative values.

2. Effect of Geometry

The effect of cylinder and sphere diameters on the critical mass is shown on Figures XXV-1 and XXV-3. Results of critical mass studies made with U^{235} have indicated that slow-neutron criticality is impossible in infinitely long water-surrounded cylinders with diameters not more than 5 inches and in air-surrounded cylinders with diameters not more than 8 inches. Safe cylinder diameters for plutonium solutions have not been directly determined, but can be shown on theoretical grounds to be not smaller than the diameters quoted above.

3. Effect of Other Elements

The presence of foreign ions in a plutonium solution increases the critical mass. This effect is due, at least in part, to the substitution of non-moderating foreign ions for some of the water moderator.

When foreign ions with neutron absorption cross-sections higher than that of water are present, the increased neutron loss results in further increase in critical mass. This effect is illustrated by Figure XXV-1 and XXV-2, which show the effect of nitrate ion on the critical mass. As shown on Figure XXV-2, the increase of the critical mass of plutonium with NO_3^- concentration is approximately linear. For 420 megawatt-day/ton plutonium the critical mass increases from 595 grams at 0 NO_3^- to 710 grams at 200 g./l. (3.2 M) NO_3^-.

4. Effect of Plutonium Concentration

Figures XXV-1 and XXV-2 show the plutonium concentration range for two of the critical mass curves. Figure XXV-3 illustrates the variation of critical mass with plutonium concentration in cylinders. The curves on Figure XXV-1 show that the lowest critical masses generally occur in the 20 to 40 g./l. range of plutonium concentrations, the minimum critical mass for 420 megawatt-day/ton plutonium (595 g.) occurring at about 36 g. Pu/l. Calculations based on the cross sections of plutonium and water for neutron capture have shown that criticality is impossible in any solution containing less than six grams of plutonium per liter. The critical mass also increases at higher plutonium concentrations (above about 40 g. Pu/l.).

5. Effect of Surrounding Materials

The critical mass values shown on Figures XXV-1, XXV-2 and XXV-3 are for assemblies surrounded by water reflectors. Critical masses of assemblies surrounded by air are higher, as illustrated by the increase in the minimum critical cylinder diameter from 5 to 8 inches when changing from water to air surroundings as noted under 2, above. The critical mass values of assemblies surrounded by stainless steel less than 3 inches thick, or by concrete, are intermediate between water-surrounded and air-surrounded values. As shown on Figures XXV-1 and XXV-2, the critical mass is increased approximately 30 g. by 0.05-in. thick stainless-steel container walls. The effects of stainless-steel container walls less than 1/2 inch thick are slight enough to cause no appreciable changes in the minimum critical cylinder diameters given above.

C. METHODS OF CRITICAL MASS CONTROL

Accumulation of a critical mass of plutonium in any process solution may be prevented by any of three methods: (a) safe solutions, (b) safe geometries, and (c) safe batches.

The method of safe solutions involves processing solutions of such composition that they cannot become critical under any possible process condition. Criticality is impossible in a safe solution because of the absorption of free neutrons by other elements in the solution. A solution cannot be considered safe without additional safeguards if any condition for the separate precipitation of the plutonium is possible.

The method of safe geometries involves handling the plutonium in isolated equipment of such size and shape that enough free neutrons escape for criticality to be impossible in any contingency that may be expected. Those solvent-extraction columns in the Redox Plant which are geometrically safe are usually referred to as safe columns. These columns are safe against slow-neutron criticality only and would have to be operated with limited-size batches (5 kg.) if fast-neutron criticality were possible.

The method of safe batches involves handling the plutonium in isolated batches which contain less plutonium than the minimum amount which will become critical under the most unfavorable conditions expected.

Application of these three general methods of critical mass control in the Redox Plant are discussed in Section D, below.

D. CRITICAL MASS CONTROL IN THE REDOX PLANT

1. General

Processing operations in the Redox Plant are conducted continuously, except for the feed preparation, plutonium concentration, and, possibly, cross-over oxidation steps. The change-over to batch operation in the plutonium concentrators is made to enable critical mass control by the safe batch method. The cross-over oxidation step was originally designed as a batch operation when a hot cross-over-oxidation procedure was believed necessary. With the subsequent satisfactory demonstration of the cross-over step at room temperature, this step may be put on a continuous basis as part of a program to increase the plutonium production capacity of the plant. This will involve receiving the IBP stream directly in the 2AF Tank instead of the IBP Receiver.

All portions of the process, except for the plutonium processing portion from the IB Column through the concentration steps, process safe solutions and thus do not require batch size control procedures. In the Second and Third Plutonium Cycles the solvent-extraction columns are geometrically safe as discussed below and thus will not require batch size control. Batch size control methods start at the IBP Receiver (or 2AF Tank) and each tank from this point on is limited to a safe batch (about 300 g.). To provide an additional safeguard, tanks which receive continuously (IBP Receiver or 2AF Tank, 3AF Tank, and 3BP Receiver) are designed to overflow before they can collect a volume of solution which will contain over 600 grams of plutonium when the plant is processing slugs with irradiation levels of up to 420 megawatt-days per ton (approximately 300 grams Pu/short ton of U). In order to maintain this safeguard at higher exposure levels, the present continuously-receiving tanks must be replaced with smaller-volume tanks or the IBP stream must be diluted with aluminum nitrate solution to a higher relative volume than that indicated on the HW #4 Flowsheet. This amount of plutonium (600 g.), while over the safe batch size specified in Subsection D2 below (about 300 g.), is safe from criticality

when plutonium from slugs with 420 megawatt-days/ton or greater pile exposure is processed.

2. Specifications for Critical Mass Control

The following definitions of safe conditions have been specified for critical mass control in the Redox process:

(a) A safe solution is one in which the ratio of plutonium to uranium is not more than the ratio in irradiated slugs. It is assumed that any condition in the Redox Plant which precipitates the plutonium will co-precipitate the neutron-absorbing uranium. Uranium-free solutions containing less than 6 g. Pu/l. are also safe as long as they remain homogeneous, but are not considered safe solutions because this safe 6 g./l. concentration could be exceeded in the event of plutonium precipitation.

(b) A safe column is one which is not more than eight inches in diameter, is spaced not closer than four diameters to any other column, and is surrounded by air. Fast-neutron criticality is not considered possible in the Redox Plant, so that a safe column is safe under all anticipated conditions.

(c) The nominal safe batch size is 300 grams of plutonium. Vessels operated on the safe batch principle must be spaced at least one foot away from any other plutonium-containing vessel.

The safe solution, safe column, and nominal safe batch size specifications are based on the material presented in Section B. The nominal batch size (300 grams) is set to provide a safety factor greater than two over the lowest critical mass (625 grams) for plutonium in Redox process streams subject to batch size control (NO_3^- concentration 0.88 M or more), when plutonium produced at irradiation levels of 420 or more megawatt-days per ton is processed. The lowest NO_3^- concentration (0.88 M) occurs in the 2BP stream. The probable exposure level at start-up of the Redox Plant is 440 megawatt-days per ton (400 grams Pu/ton U) or greater. Slight deviations from the nominal 300-gram batch size will be encountered, since batch collection will be by volume and the plutonium content will vary slightly from batch to batch. The actual permissible plus deviation from the 300-gram size allowed before it will be necessary to split the batch will be determined after the plant goes into operation. The allowable plus deviation will probably be at least 12 grams, giving a tentative maximum batch content of 312 grams (one-half of the 625 gram critical mass for 2BP), and can possibly be much higher (350 to 400 g.) when the effects of precipitate configurations and surroundings other than pure water are given full account.

To reach a critical accumulation of plutonium in the Redox Plant with the 300 gram batch size specified above a series of unusual happenings such as the following must occur together: the plutonium from two batches must (a) mix, (b) totally precipitate, (c) form a 12 to 15-inch sphere surrounded on all sides by at least 4 inches of water, (d) be uniformly suspended in the spherical shape at approximately the optimum Pu concentration (20 to 40

g. Pu/l.), and (e) contain no nitrate or other foreign solutes. The probability of these or other off-standard circumstances which would result in criticality occurring together is so exceedingly small that in effect the safety factor with a 300-gram batch size is very much larger than two.

No critical mass specifications are given for pipe lines in the Redox Plant, as all pipes are small enough to have safe geometry and to have no appreciable effect upon critical mass control in near-by vessels.

3. Application to the Redox Plant

A 400 g./ton (400 g. Pu/short ton U) plutonium concentration in irradiated slugs gives maximum process-stream plutonium concentrations of approximately 1.3 grams per liter (in the 2BP and 3BP streams), except in the plutonium concentration step, where a concentration of 10 g. Pu/l. is reached. As pointed out in Subsection 1, above, solutions containing not more than 6 g. Pu/l. are safe from criticality regardless of the quantity of plutonium present except in case of accidental precipitation of the plutonium followed by arrangement into near-optimum configuration.

The feed preparation step, the first solvent-extraction cycle, except for the IB Column scrub section, the second and third uranium solvent-extraction cycles, and the uranium concentration steps rely on critical mass control by the use of safe solutions. All streams in these cycles have a uranium-to-plutonium ratio not less than the ratio in irradiated slugs and are therefore safe from criticality even under conditions of accidental precipitation, the uranium being expected to precipitate with the plutonium.

The IB Column scrub section, the cross-over oxidation step, the second and third plutonium solvent-extraction cycles, and the plutonium concentration step rely on safe columns and on safe (limited size) batches for critical mass control.

The plutonium-cycle solvent-extraction columns conform to the safe column specifications and are considered safe even under conditions of accidental plutonium precipitation.

All other plutonium-cycle vessels are normally operated so as not to contain more than 300-gram nominal batch size of plutonium. Continuously-receiving tanks (IBP Receiver or 2AF Tank, 3AF Tank, and 3BP Receiver) have an additional safety factor. Because they are more liable to accidental overfilling, these vessels are operated so that they will overflow before they can contain a volume of solution which would normally contain 600 grams. Unless the present continuously-receiving tanks are replaced with tanks of smaller volume this requires that the IBP stream be diluted with additional aluminum nitrate solution when the plant is processing slugs with an exposure level of over 420 megawatt-days per ton. This is accomplished either by increasing the relative flow rate of the IBX stream or by adding aluminum nitrate solution (IBP Butt) to increase the volume of the IBP solution. Any

off-standard Redox plutonium stream to be re-processed through the plutonium cycles is similarly diluted with aluminum nitrate solution to the required extent.

Undetected precipitation constitutes a potential criticality hazard in batch-operated vessels as the resulting plutonium holdup could make it possible to exceed the maximum batch size. For this reason plutonium stream samples must be taken periodically so that material balances can be made to detect plutonium holdup. Procedures for critical mass control applied specifically to the plutonium solvent-extraction cycles and the plutonium concentrators are discussed in Chapters VI and VII, respectively.

E. CONSEQUENCES OF EXCEEDING THE CRITICAL MASS

The accidental accumulation of a critical mass of plutonium in the Redox Plant can result only from a number of unusual events happening together, such as those listed in Subsection D2, above, and is therefore extremely unlikely. If a critical mass is accidentally accumulated in any process vessel, the outcome will depend largely upon the rate at which the supercritical conditions are attained. The possibilities range all the way from (a) simmering at a temperature slightly above that of the room, through (b) slow boiling, and (c) boiling at a pressure high enough to eject plutonium solution through the vent system to the atmosphere, to (d) a steam explosion with a temperature of at most 5000°C. Cases (c) and (d) are considered extremely unlikely. The most extreme conditions believed at all likely if the critical mass is exceeded are: (a) development of about two atmospheres of absolute pressure for less than 1/10 of a second in the process vessel and (b) radiation sufficient to give a man located behind 1-1/2 feet of concrete shielding a dosage of 70 roentgens of gamma radiation.

REFERENCES

(1) 3-2549 — Limiting Mass V. J. A. Wheeler. Hanford Works. June 4, 1945.

(2) HW-14460 — Critical Mass Control -- Redox Process Design. R. H. Beaton. Sept. 13, 1949.

(3) HW-18791 — Summary of P-11 Results. P. F. Gast. Sept. 11, 1950.

(4) K-375 — Radiation Dosage from Chain Reactions. N. C. Edlund and S. Visner. March 23, 1949.

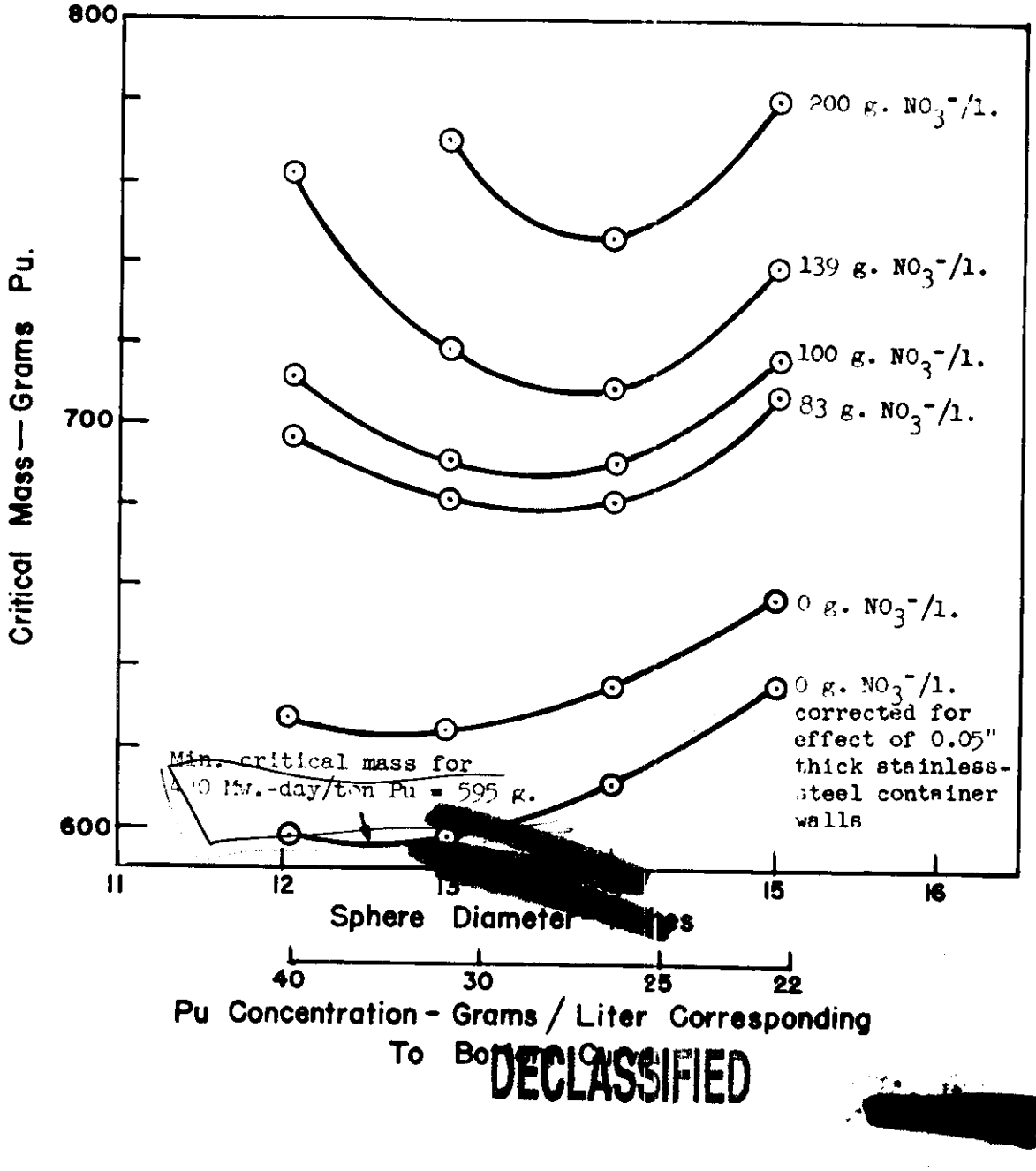
[redacted]

FIGURE 1

CRITICAL MASS OF PLUTONIUM

EFFECT OF SPHERE DIAMETER AND TOTAL NITRATE CONCENTRATION

This figure is based on preliminary data obtained from the Pile Technology Division. The curves are for stainless-steel spheres, completely surrounded by a water reflector, and containing plutonium from slugs with 420 megawatt-days/ton pile exposure, in aqueous nitric acid solutions. Correction for the effect of the 0.05-in. thick stainless-steel container walls has not been made, except where noted. Some of the points shown represent direct experimental results while others were obtained by interpolation and/or application of certain correction factors.



[redacted]

1204

HW-18700

[redacted]

DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

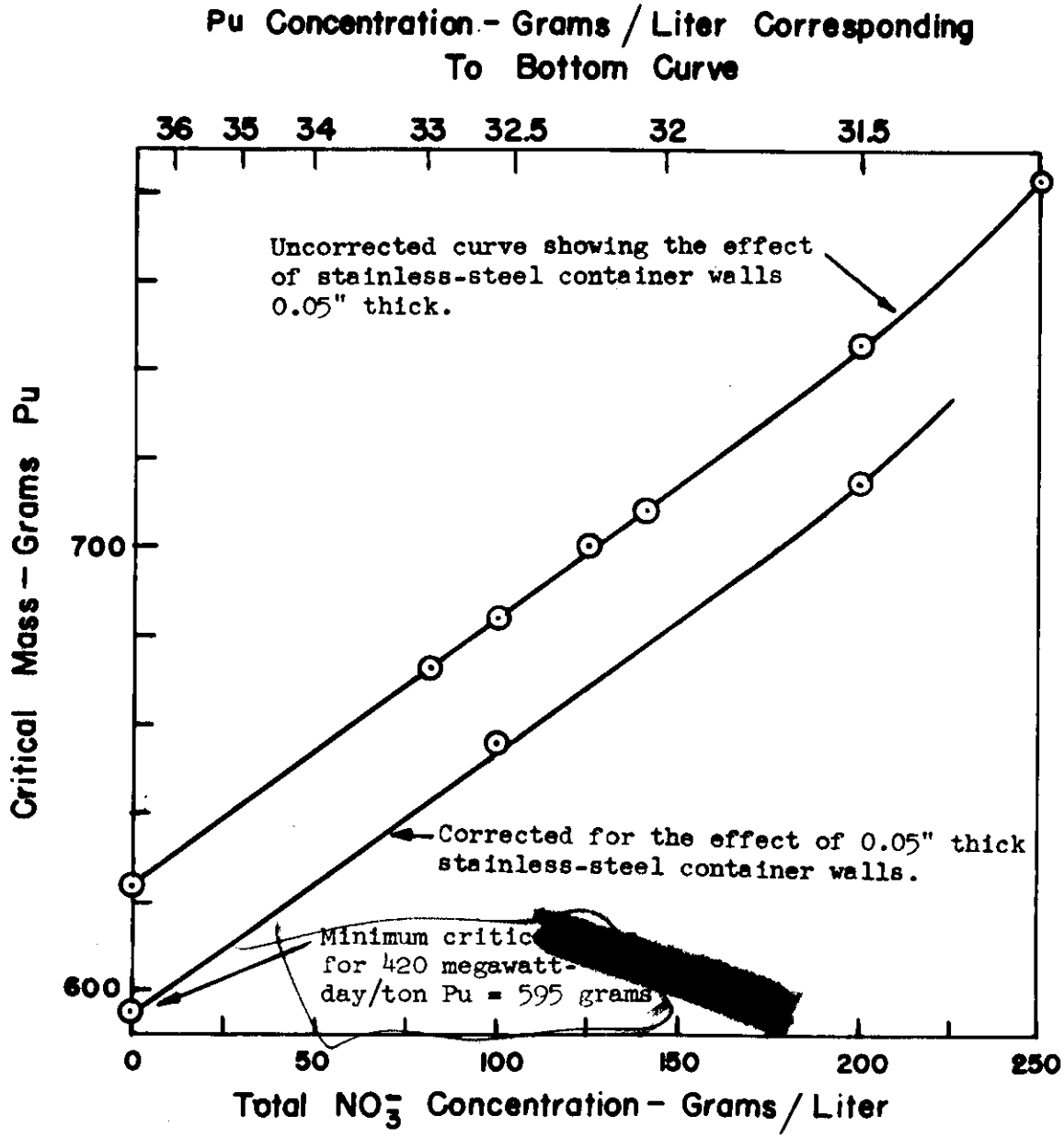
DECLASSIFIED

Figure XXV-2

CRITICAL MA[redacted]PLUTONIUM

EFFECT OF TOTAL NITRATE CONCENTRATION IN OPTIMUM DIAMETER SPHERES

This figure is based on preliminary data obtained from the Pile Technology Division. The curves are for optimum-diameter (12 to 15 inch) stainless-steel spheres, completely surrounded by a water reflector, and containing plutonium from slugs with 420 megawatt-days per ton pile exposure, in aqueous nitric acid solutions. Points shown are the minimum points from curves similar to those shown on Fig. XXV-I.



1208

HW-18700

[redacted]

DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

DECLASSIFIED

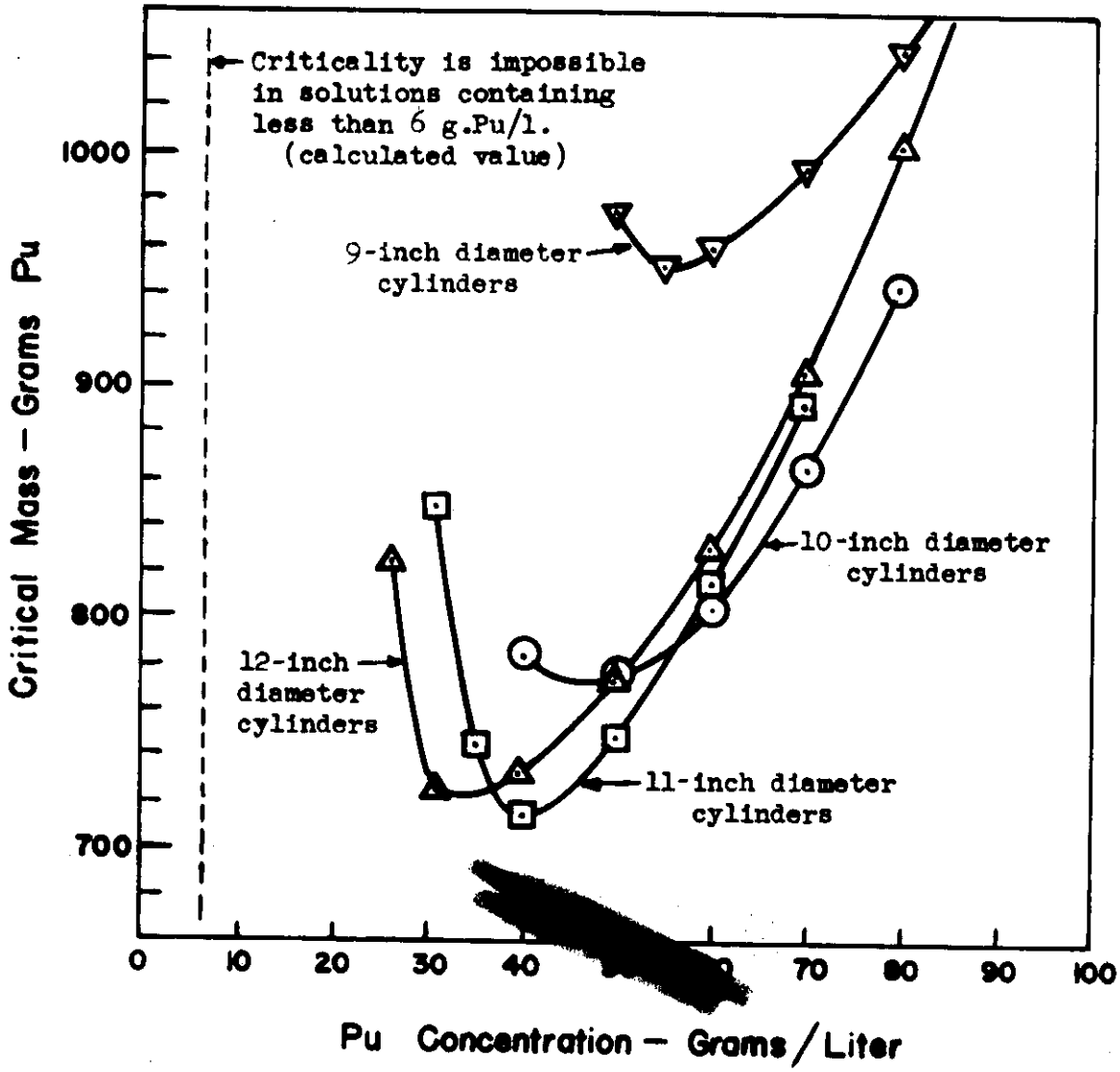
[redacted]

Figure XXV-3

CRITICAL [redacted] PLUTONIUM

EFFECT OF PLUTONIUM CONCENTRATION IN CYLINDERS

This figure is based on preliminary data obtained from the Pile Technology Division. The curves are for stainless-steel cylinders, completely surrounded by a water reflector, and containing plutonium from slugs with 385 megawatt-days per ton pile exposure in aqueous solutions containing approximately 2.0 M nitrate ion. Correction for the effect of the stainless-steel container walls has been made for all curves. Points shown were obtained by applying a stainless-steel correction factor to direct experimental results.



[redacted]

[redacted]

1210

HW-18700

[redacted]

DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

DECLASSIFIED

APPENDIX A

NUCLEONICS

CONTENTS

A. FUNDAMENTAL NUCLEAR PHYSICS

1. Atomic Structure

According to the current conception of atomic structure, the atom consists of neutrons, protons, and electrons. The neutrons and protons form an assemblage called the nucleus around which the electrons move in orbits determined by electrical forces. Simplified schematic drawings of the structure of several atoms, indicating the components of the nucleus and the orbital paths of the electrons, are shown in Figure XXVI-1.

The weight of a neutron is very nearly equal to that of a proton, each having essentially unit weight in the atomic scale. In comparison, the weight of an electron is almost negligible, being only 1/1840 that of a proton or neutron. Each proton carries one positive charge and each electron, one negative charge. Neutrons are electrically neutral. The electrical attraction between the positively charged protons of the nucleus and the negatively charged electrons of the orbits holds the atom together.

The forces which act between the orbital electrons and the nucleus are the familiar electrical forces of attraction between unlike charges and repulsion between like charges. This type of force does not, however, explain the cohesiveness of a nucleus which contains a number of positively charged massive protons in a volume only 10^{-12} times as large as the volume of the entire atom. These nuclei are held together by forces which are peculiar to nuclei; strong attractive forces exist between similarly charged protons, between electrically neutral neutrons, and between neutrons and protons within the nuclear volume.

The diameter of an atom is approximately 10,000 times as great as the diameter of its nucleus. Because of this fact and the extreme small size of the electrons, an atom is mostly empty space with minute electrons revolving about an extremely dense nucleus. It might be noted that the atomic diameter of the common isotope of uranium (atomic weight 238) is approximately 10^{-8} centimeters and the nuclear diameter, approximately 10^{-12} centimeters.

The nucleus is characterized by the atomic number and the mass number. The atomic number, Z, is a direct expression of the number of positive charges in the nucleus and is therefore equal to the number of protons. The mass number, A, is numerically equal to the total number of particles in the nucleus, that is, the sum of the neutrons plus protons. The absolute mass, M, of an atom is very nearly equal to the mass number.

The number of electrons in a neutral atom determines the chemical properties of the element. Because the number of protons is equal to the number of electrons, one may say also that the number of protons in the nucleus determines the chemical properties of the element. It is possible

to have different numbers of associated neutrons and therefore different absolute masses, M, in atoms of the same element. These different species of the same element are called isotopes. Two isotopes of boron are shown in Fig. XXVI-1. The atomic weight, W, of a given element is dependent on the relative abundance of its different isotopes. The mass numbers and relative abundance of the known naturally-occurring isotopes are given in Table XXVI-2. The atomic weight of an element may be precisely calculated if the relative abundance and absolute mass, M, of each isotope are known.

Since the number of protons in various isotopes of a given element are exactly the same, the chemical properties of isotopes are identical. Therefore, they cannot be separated by ordinary chemical methods but only by procedures which take advantage of the difference in physical properties due to the difference in absolute mass of the atoms.

2. Radioactivity

The ratio of the number of neutrons to the number of protons in stable nuclei falls in a fairly well-defined and rather narrow range of values. If for some reason the ratio falls outside this range, the nucleus is unstable. Unstable nuclei occur in nature and also frequently result from nuclear reactions. An unstable nucleus is said to be "radioactive". It tends to adjust its neutron-proton ratio with energy emission to acquire stability by a process called "radioactive decay".

In the process of acquiring stability most radioactive materials emit either beta particles (electrons) or positrons (positively charged particles of mass similar to the electrons), which are often accompanied by the emission of gamma rays (high-energy electromagnetic rays). Furthermore, many of the naturally radioactive, and some of the artificially radioactive, elements emit alpha particles (helium nuclei of mass four and positive charge two). The rate at which these particles are emitted is known as the radioactivity, or just the "activity", of the material. When the rate is high, the activity is said to be high, and vice versa. Each radioactive species has a characteristic rate at which its activity decreases. The rate of decay is usually expressed in terms of the time required for the activity to decrease by one-half. This time is called the half life of the species. Half lives of artificially radioactive species range from fractions of seconds to millions of years. A chart of the three series of natural radioactivities and important related isotopes artificially produced is shown as Figure XXVI-3.

The activity of a radioactive material is expressed in terms of the number of disintegrations of its atoms which occur each second. When the number of disintegrations per second is equal to 3.7×10^{10}, which is the number of atoms disintegrating per second in one gram of radium, the sample is said to have one curie of radioactivity.

3. Induced Nuclear Reactions

Nuclear reactions which change the atomic number, that is, the number of protons in the nucleus, actually convert one element into

another. This process is known as artificial transmutation. Such changes can be accomplished by bombarding the nucleus with suitable projectiles such as neutrons, protons, deuterons, and alpha particles. A deuteron is the nucleus of the heavy hydrogen atom containing one neutron and one proton. With the exception of neutrons, all of the aforementioned projectiles are positively charged, and tend to be repelled by the positively charged protons of the nucleus at which they are aimed. Therefore, it is difficult to introduce them into the nucleus unless they are moving at extremely high velocities and with great kinetic energy. However, most "atom smashers" such as the cyclotron are based on the principle of imparting extremely high velocities to these positively charged particles and using them as projectiles to enter the nucleus by impact.

Also, it has been found that neutrons are very effective in entering nuclei. This is due to the fact that they carry no free electric charge and consequently are not repelled by the positively charged protons of the nuclei with which they come in contact. As a result it is not necessary that the neutrons be at a high velocity. In fact, in plutonium production, it is essential that they have a relatively low velocity (approximately 2 miles/sec.).

The most important types of nuclear reactions involving neutrons are the following:

(a) Impact without capture of the incident neutron.

(1) Elastic impact, with no emission of particles or radiations.

(2) Inelastic impact accompanied by emission of gamma rays. These rays are emitted by the excited nucleus as a means of disposing of the energy acquired in the collision.

(b) Capture of the incident neutron followed by emission of a nuclear particle (e.g., proton, alpha particle, or neutron).

(c) Simple capture of the incident neutron without emission of a nuclear particle but with the emission of gamma rays. Where an unstable isotope is produced, the nucleus tends to stabilize itself by emission of a beta particle (electron). Gamma rays are often emitted simultaneously with the beta particles.

(d) Capture of the incident neutron followed by immediate fission or splitting of the nucleus into two new nuclei, accompanied by the emission of several free neutrons. Beta particles and gamma rays are also emitted due to the radioactive decay of newly created unstable nuclei.

4. Mass and Energy Relationships

The study of nuclear reactions is entirely parallel to the more familiar study of chemical reactions. One meets such fundamental concepts as the equation of the reaction, the process of balancing the equation

with respect to quantities which are conserved in the reaction, and the rates of the reaction. In nuclear physics the nucleus is expressed by a symbol which consists of the chemical abbreviation for the element with the atomic number as a pre-subscript and the mass number as the post-superscript; for example:

$$_{92}U^{238};\quad _{5}B^{10};\quad _{1}H^{1}.$$

In this manual, the pre-subscript is sometimes omitted.

Two different notations are common in expressing the equation of a reaction. For example, the reaction between a neutron and a boron nucleus ($_5B^{10}$) can be written in the following ways:

$$_{5}B^{10} + {}_{0}n^{1} \longrightarrow {}_{3}Li^{7} + {}_{2}He^{4} + Q$$

boron neutron lithium helium (alpha particle) energy

or

$$_{5}B^{10}\ (n, \alpha)\ {}_{3}Li^{7}.$$

In the latter method of writing the reaction, the first symbol within the parenthesis indicates the projectile and the last symbol indicates the emitted particle.

In every nuclear reaction the total number of particles, protons plus neutrons, is conserved. The total electrical charge is also conserved. For example, in the above reaction the balance is as follows:

	Left Side	Right Side
Total number of neutrons and protons	10 + 1	7 + 4
Total charge	5 + 0	3 + 2

As in the case of chemical reactions, the energy balance of a nuclear reaction provides an indication of the ease with which the reaction can be made to proceed. The reaction is exoergic or enoergic, by analogy with chemical reactions, according to whether the energy, Q, of the reaction is positive or negative. In the energy balances of nuclear reactions there is a very striking equivalence between mass and energy which is not detected in chemical reactions because of the relatively small energies involved in chemical as compared with nuclear processes. The energy unit of nuclear physics is the electron-volt, abbreviated e.v. The electron-volt is generally defined as the amount of energy which a singly charged particle, for example a proton or electron, has acquired after falling through a potential difference of one volt. The unit has acquired this form because of the convenience of expressing the energy of artificially accelerated atomic projectiles in terms of the voltage used to accelerate them. This unit of energy is now universally used in nuclear physics even when artificial acceleration is not involved. In

many problems the unit electron-volt is inconveniently small. For this reason the million-electron-volt, abbreviated M.e.v. and equal to 10^6 e.v., is very often used. The comparative size of the electron-volt and the more familiar units of energy is presented in the following tabulation:

1 e.v. = 1.6×10^{-12} erg
1 M.e.v. = 1.6×10^{-6} erg
1 M.e.v. = 1.18×10^{-13} ft.-lb.
1 M.e.v. = 3.83×10^{-17} kg.-cal.
1 M.e.v. = 4.45×10^{-20} kw.-hr.

The energy of thermal agitation of molecules is approximately 1/40 e.v.; the energy of alpha particles from naturally radioactive elements is about 5 M.e.v.; and the energy of alpha particles accelerated by the larger cyclotrons is as high as 40 M.e.v. By contrast to the above, the energy released in the fission of a uranium nucleus is approximately 200 M.e.v.

The equivalence of mass and energy, referred to above, is a development of the theory of relativity. It is expressed by the relation:

$$E = mc^2$$

where E is the energy in ergs; m, the mass in grams; and c, the velocity of light in cm./sec.

Mass can be converted into energy and energy into mass. When mass disappears in a reaction, it appears as energy of the reaction. The equivalence between energy in electron-volts and mass in atomic units is set forth in the following relations:

One absolute mass unit = 931 M.e.v.
1 M.e.v. = 0.00107 absolute mass units
One absolute mass unit = 1.66×10^{-24} g.
The energy equivalent of the mass of an electron = 0.51 M.e.v.

As an example of the use of the mass-energy equivalence relation, it is applied to predict the energy release of the neutron-boron reaction. The reaction is:

$$_5B^{10} + {}_0n^1 \text{ (slow)} \longrightarrow {}_3Li^7 + {}_2He^4 + \text{Energy}$$

Based on the atomic weights of these atoms, the mass-energy balance may be stated as follows:

$10.01605 + 1.00893 \longrightarrow 7.01804 + 4.00389 + \text{Energy};$

or $11.02498 \longrightarrow 11.02193 + \text{Energy};$

and Energy = 0.00305 units of atomic weight.

Therefore, the predicted energy of reaction = $\frac{0.00305}{0.00107}$ = 2.85 M.e.v.

The predicted energy release of 2.85 M.e.v. agrees with the experimentally observed energies of the product nuclei.

B. NUCLEAR REACTIONS OF URANIUM

1. Nuclear Fission

A reaction which results in the splitting of a nucleus into two approximately equal parts is called fission. One of the most important fission reactions occurs in uranium nuclei. In the most prominent reaction leading to fission in naturally occurring uranium, an atom of isotope 235 captures a neutron to form an excited compound nucleus U^{236}. This nucleus decays predominantly by fission but also by gamma emission, with the result that a small amount of rather stable (i.e., long-lived) U^{236} is formed. The fission act of the excited U^{236} nucleus may be likened, by anology, with the behavior of a liquid drop of matter in vibration. If, during these vibrations, there is a sufficient separation of the two nuclear masses so that the electrostatic forces of repulsion between them exceed the cohesive forces of "surface tension" for the whole nuclear mass, then fission occurs. However, if the excess energy given to the nucleus upon capture of the neutron can be released as gamma radiation from the vibrating compound nucleus, then a condition of stability may be attained without the occurrence of fission. The sequence of events occurring in fission are illustrated in Figure XXVI-4.

The new nuclei produced by the fission reaction belong to elements in the middle of the atomic series. The importance and great value of this reaction result from two of its features. First, each fission is accompanied by the largest energy release yet obtained from a nuclear reaction. Second, the fission reaction releases neutrons in amounts sufficient to make the fission reaction self-sustaining when the conditions are properly controlled. The reactants and products of fission can be presented in the form:

Uranium nucleus + single neutron ⟶ (a) two new nuclei; (b) several free neutrons; (c) large amount of energy

At the instant of fracture the highly excited nuclear fragments have sufficient energy to eject neutrons. A typical reaction might be:

$$_{92}U^{235} + {}_{0}n^{1}\ (\text{slow}) \longrightarrow (_{92}U^{236}) \longrightarrow {}_{36}Kr^{94}\ (\text{highly excited}) + {}_{56}Ba^{142}\ (\text{highly excited})$$

On the average, between two and three fast neutrons are emitted by the excited nuclei immediately on fission. The emission of these several neutrons for the single neutron captured makes self-sustained fission

possible. For example:

$$_{36}Kr^{94} + {}_{56}Ba^{142} \longrightarrow {}_{36}Kr^{92} + {}_{56}Ba^{141} + 3\ {}_{0}n^{1} + \text{Energy}$$

Even following neutron release, the products are unstable, due to the unsatisfactorily high neutron to proton ratios of these nuclei. The unstable krypton and barium nuclei decay by the emission of beta particles, resulting in conversion of neutrons to protons, in a so-called "fission decay chain". The decay continues from element to element until a stable isotope is reached. For example, the above unstable nuclei decay with beta and gamma emission in the following possible fission decay chains:

$$_{36}Kr^{92} \xrightarrow{\beta^-} \text{Rb} \xrightarrow{\beta^-} \text{Sr} \xrightarrow{\beta^-} \text{Y} \xrightarrow{\beta^-} {}_{40}Zr^{92} \quad \text{(stable)}$$

$$_{56}Ba^{141} \xrightarrow{\beta^-} \text{La} \xrightarrow{\beta^-} \text{Ce} \xrightarrow{\beta^-} {}_{59}Pr^{141} \quad \text{(stable)}$$

The tremendous energy released in the fission process makes the reaction important as a source of energy for special applications. The energy which is released arises from the excess mass of the original uranium nucleus and neutron over that of the final stable products, in accordance with the mass-energy equivalence. An estimate of the magnitude of the energy released per fission can be obtained by considering the reaction already referred to:

$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow (\text{fission and neutron emission followed by decay to stable products}) \longrightarrow {}_{40}Zr^{92} + {}_{59}Pr^{141} + 3\ {}_{0}n^{1}$$

To compute the amount of mass which is converted to energy, the difference in the sums of the atomic weights is obtained.

Atomic Weight of Original Particles		Atomic Weight of Final Particles	
$_{92}U^{235}$	235.1240	$_{40}Zr^{92}$	91.9420
$_{0}n^{1}$	1.0089	$_{59}Pr^{141}$	140.9590
		$_{0}n^{1}$ (3)	3.0267
	236.1329		235.9277

Mass difference = 0.205 units of atomic weight

Energy released per fission = $\frac{0.205}{0.00107}$ = 190 M.e.v.

(0.00107 mass unit = 1 M.e.v.)

The estimated energy release is close to the accepted average release of 200 M.e.v. per fission. Most of the energy appears as energy of the large fission fragments. This energy is dissipated by heating of the stopping materials. The remainder of the energy appears as energy of the gamma rays, beta particles, and neutrons which accompany the process. The distribution of the energy among the various particles is as follows:

Kinetic energy of fission fragments	159 M.e.v.
Gamma radiations from fission products	23 M.e.v.
Beta radiation from fission products	11 M.e.v.
Kinetic energy of neutrons	7 M.e.v.
Total	200 M.e.v.

An interesting and important feature in the decay of the fission products is that, in the case of several of these products, the decay proceeds with emission of neutrons. Radioactive bromine and iodine formed in the initial fission reaction have been identified as neutron emitters. At least two other neutron emitters are present but they have not been identified. Neutron emission occurs in those cases in which the excess energy of a nucleus is so great that the excess cannot be dissipated quickly enough by beta and gamma emission alone. The neutrons which are emitted in this fashion are called "delayed neutrons". The growth and decay of delayed neutron activity is very similar to that of beta activity.

2. Formation of Plutonium

Plutonium is formed from uranium by nuclear reactions involving isotope U^{238}. Thus, slow neutrons and resonance neutrons may be captured by this nucleus to give U^{239}, which decays by beta particle emission to element 93, or neptunium. The beta-unstable neptunium isotope, N_p^{239}, then decays to element 94, which is called plutonium. The series of reactions leading to the formation of plutonium is given as follows:

$$_{92}U^{238} + {}_0n^1 \longrightarrow {}_{92}U^{239} + \gamma$$

$$_{92}U^{239} \xrightarrow[t_{\frac{1}{2}}\ 23.5\ \text{min.}]{} {}_{93}Np^{239} + {}_{-1}\beta$$

$$_{93}Np^{239} \xrightarrow[t_{\frac{1}{2}}\ 2.33\ \text{days}]{} {}_{94}Pu^{239} + {}_{-1}\beta + \gamma$$

Plutonium itself is radioactive and decays by alpha particle emission to uranium, according to the reaction:

$$_{94}Pu^{239} \xrightarrow[t_{\frac{1}{2}}\ 24{,}300\ \text{yr.}]{} {}_{92}U^{235} + {}_2He^4$$

Since the half life of Pu^{239} is 24,300 years, it is relatively stable and can be manufactured and retained in quantity. However, to

produce the material, an intense source of neutrons must be available, since 2.52×10^{21} neutrons are required for each gram of plutonium. Such a source of neutrons is provided by the excess neutrons from the fission of isotope U^{235}. Thus, the process for producing plutonium consists of providing the conditions necessary for slow neutrons to start the fission of isotope U^{235} and then to slow down the resulting fast neutrons so that some of them are captured by the U^{238} nucleus. At the same time, at least one new neutron from each atom of U^{235} fissioned must be available to continue the fission of more U^{235} and so maintain the chain reaction.

3. The Pile

The structure in which the uranium chain reaction for the production of plutonium is carried out is called a pile. The Hanford piles consist of structures made up of graphite blocks arranged in the form of rectangular prisms approximately 36 feet wide and high and 28 feet long. The graphite prisms are pierced with 2004 holes in the form of cylindrical channels. Each channel is lined with an aluminum tube in which the cylindrical aluminum-jacketed uranium pieces, called "slugs", are placed. The heat of the pile reaction is removed by cooling water which is forced at high velocity through an annular space between the slugs and the tube.

The reaction rate (or power level) of the Hanford piles is determined from the temperature rise and known flow rate of the pile cooling water, and is measured in megawatts. The irradiation that the uranium receives in the pile is measured in megawatt-days per ton of uranium. The amount of plutonium produced in the uranium is dependent upon the irradiation the slugs receive. The relation between the irradiation level, in megawatt-days per ton of uranium, and the grams of plutonium produced per ton of uranium is approximately as follows:

	Irradiation Levels in Megawatt-Days/Short Ton of Uranium			
	200	400	600	900
Grams Pu/Megawatt-Day	0.935	0.905	0.88	0.84
Grams Pu/Short Ton U	185	360	530	760

Plutonium isotopes other than Pu^{239} as well as higher transuranic elements, such as americium and curium, are also produced in small quantities by neutron reactions in the pile. Americium and curium, both alpha-particle emitters, are troublesome to separations processes in that, unless properly corrected for, they confuse the routine radioassay for plutonium in the first process waste stream. Other plutonium isotopes (such as Pu^{240}) act to inhibit the reactivity of Pu^{239}. These undesirable isotopes are produced in increasing quantities with increased exposure of uranium in the pile, in megawatt-days/ton of uranium.

C. THE FISSION PRODUCTS

1. Formation and Fission Yield

The two nuclear fragments which are formed during the fission of a heavy isotope, such as U^{235}, are called fission products. The masses (and mass numbers) of these fragments vary considerably because of variations in asymmetry of the uranium nucleus at the instant of fission. In all cases, however, the sum of the mass numbers of the two fragments plus the liberated neutrons must total to 236, the mass number of the excited compound uranium nucleus. Thus, if two neutrons are liberated in a given fission reaction, one may find a large number of possible combinations of mass numbers, such as 160-74, 159-75, 158-76. . . 140-94, 139-95, 138-96 . . . . . 118-116, 117-117. The probability of a fission fragment with a given mass number resulting from fission is called the fission yield. Thus a 5.6% fission yield for mass number 135 indicates that for every 100 atoms of U^{235} which fission, 5.6 fission fragments of mass number 135 are formed. The fission yield is based on mass number rather than atomic number because the elemental composition of the fission products changes with time as a result of beta decay. The U^{235} fission yield versus mass number curve, based on data obtained by Plutonium Project Chemists[1], is shown on Figure XXVI-5.

All of the radioactive fission products which have been identified thus far in pile fission material are shown in Figure XXVI-6. The beta decay of a given chain proceeds upward on this figure. For example, the table shows that the decay of a fission fragment of mass number 105 proceeds as follows:

$$_{42}Mo^{105} \xrightarrow{\beta^-} {}_{43}Tc^{105} \xrightarrow{\beta^-} {}_{44}Ru^{105} \xrightarrow{\beta^-} {}_{45}Rh^{105} \xrightarrow{\beta^-} Pd^{105} \text{ (stable)}$$

The approximately 180 known radioactive fission products occur in more than 60 decay chains, an average of approximately 3 members per chain. Theoretically, there should be, on the average, between 3 and 4 members per decay chain. The fact that the average chain length is only about 3 indicates that there are other radioisotopes which have not yet been identified. Most of these fission products, however, are very short-lived or very long-lived so that it is difficult to conduct experimental studies to identify them.

2. Fission Products Important in Plant Operations

In normal operation of the plant, the uranium metal slugs are irradiated in the piles for periods ranging from about 9-1/2 months to about two years and then are stored for a period of 40 to 90 days before being processed. The variations in irradiation time are necessary to balance the effects of differences in neutron flux at different points in the pile and differences in pile power level (normally 300 to 500 megawatts). A "cooling" time of 40 to 90 days is normally used so that gamma-emitting 2.33-day Np^{239} will decay to plutonium and 8.0-day I^{131} will decay to low enough concentration levels that the I^{131} discharged to the atmosphere during the separations processing will not constitute a health hazard in surrounding areas. Also, other short-lived activities (such as 11-hour Y^{93}, 17-hour Zr^{97}, etc.) decay to negligible levels.

The important long-lived activities which remain after the "cooling" period are tabulated in Chapter II.

3. Activity and Heating Effects of Fission Products

During the operation of the pile there are 3×10^{10} fissions/second occurring for each watt of pile power. Thus, for a pile operating at 325 megawatts there are $325 \times 10^6 \times 3 \times 10^{10} = 9.75 \times 10^{18}$ fissions/second, 8.4×10^{23} fissions/day, or a total of 1.6×10^{24} fission fragments/day. Since all of these fission products do not decay immediately to stable isotopes, radioactive isotopes accumulate in the pile metal. The rate of accumulation is governed by the pile power, and the total radioactivity is a function of the time of operation.

The overall change in the radioactivity of irradiated uranium, as measured in curies, is not a simple function of the number of fission fragments which have been produced, since (a) the half life of each of the many radioisotopes governs its disintegration rate and (b) many radioisotopes decay to daughter activities which contribute to the overall disintegration rate. The radioactivity of individual fission products in the uranium may be calculated by use of the following equations:(5)

$$A = k\left(1 - e^{-\lambda_p t_i}\right)\left(e^{-\lambda_p t_c}\right) \qquad (1)$$

and

$$B = k\left(\left[1 - e^{-\lambda_d t_i} - \frac{\lambda_d}{\lambda_d - \lambda_p}\left\{e^{-\lambda_p t_i} - e^{-\lambda_d t_c}\right\}\right] e^{-\lambda_d t_c} + \frac{\lambda_d}{\lambda_d - \lambda_p}\left\{1 - e^{-\lambda_p t_i}\right\}\left\{e^{-\lambda_p t_c} - e^{-\lambda_d t_c}\right\}\right) \qquad (2)$$

where A = activity in curies/ton U from parent isotope;

B = activity in curies/ton U from daughter isotope;

t_i = irradiation time;

t_c = "cooling" time;

λ_p = decay constant of parent isotope;

λ_d = decay constant of daughter isotope;

(decay constant = $\frac{0.693}{\text{half life}}$)

k = 0.86×10^6 (fission yield) ($\frac{\text{megawatt-days/ton U}}{\text{days exposure}}$);

e = the base of natural logarithms = 2.718.

Half lives, irradiation time, and "cooling" time must be expressed in the same time units (i.e., hours, days, or years). When using these equations to calculate radioactivity in the metal feed to the separations plants, only the relatively long-lived fission products and those daughter fission products which have long-lived parents need be considered, as may be seen from Table II-5 in Chapter II.

As an example of the use of Equation (1), it is used to calculate the radioactivity from long-lived Sr^{89} in uranium slugs which have received an integrated exposure of 400 megawatt-days/ton over a period of 360 days in the pile and have then been "cooled" for 90 days as follows:

Sr^{89} half life = 54 days;

Sr^{89} fission yield = 4.7%.

$$A = 0.86 \times 10^6 (0.047)\left(\frac{400}{360}\right)\left[1 - e^{-\left(\frac{0.693}{54}\right)(360)}\right]\left[e^{-\left(\frac{0.693}{54}\right)(90)}\right]$$

$$= 4.5 \times 10^4 \left(\ 1\ \right)(0.315) = 1.4 \times 10^3 \text{ curies/ton U.}$$

The overall change in the radioactivity of metal which has been irradiated in the pile and then removed, and the decay of the radioactivity of individual fission products are discussed in Chapter II.

The heating effects of the radioactive fission products may be calculated from the energies and absorption characteristics of their beta and gamma radiations. The power developed by fission-product radiations, without considering their absorption in surrounding matter, may be obtained from Figures XXVI-7, XXVI-8, and XXVI-9. In the example below, Figure XXVI-7 is used to calculate the total heat generated in an underground storage tank.

One 750,000 gal. waste storage tank, when full, contains the fission products from approximately 250 tons of irradiated uranium. If this uranium was irradiated for 100 days at 400 megawatts in a 200-ton pile and the average time elapsed since its discharge from the pile is 175 days, it may be determined from Figure XXVI-7 that the total watts of fission-product radiation power per 200 tons of uranium processed per watt of pile power level is 1.55×10^{-4} watts. The total power is then

$$\frac{(1.55 \times 10^{-4})(400 \times 10^6)(250)}{(200)} = 7.75 \times 10^4 \text{ watts,}$$

or 264,000 B.t.u./hr. On the assumption that all of this energy is absorbed in the tank liquid, approximately 250 pounds of water are being evaporated and refluxed back to the tank by the air condenser every hour.

REFERENCES

(1) Author not stated, J. Am. Chem. Soc., 68, 2411, (1946).

(2) Author not stated, General Electric Research Laboratory Chart of the Nuclides. Dec., 1949.

(3) HW-10475-C H.E.W. Technical Manual, Section C. Author not stated. Nov., 1945.

(4) HW-10475-B H.E.W. Technical Manual, Section B. Author not stated. Aug., 1946.

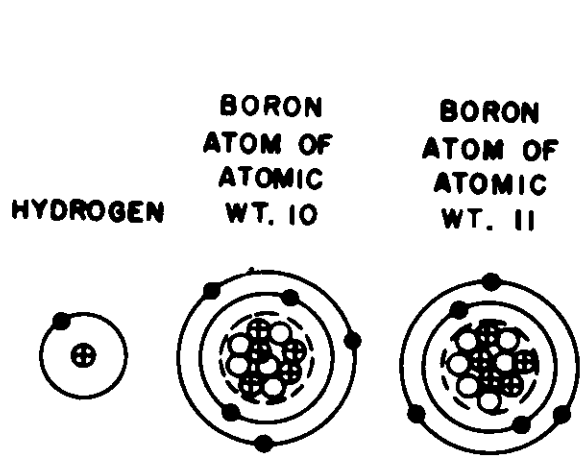
(5) HW-11528 Activity of Fission Products. M. Garbrecht and P.R. Gillette. Nov. 11, 1948.

[redacted]

[redacted]

Figure XXVI-1

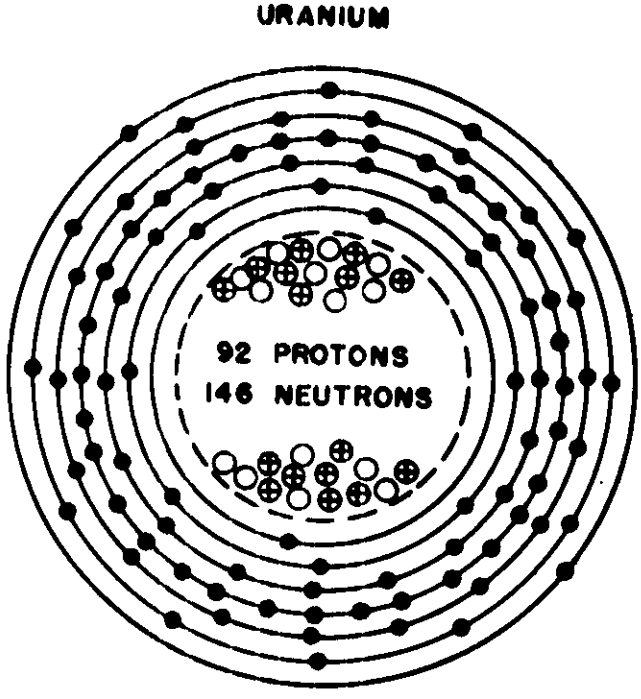
COMPONENTS OF ATOMS



(THE NUCLEUS IS SHOWN EXAGGERATED IN SIZE RELATIVE TO ELECTRON ORBITS)

LEGEND

- ○ NEUTRON
- ⊕ PROTON
- ● ELECTRON



SEVEN ORBITS CONTAINING A TOTAL OF 92 ELECTRONS

DESIGNATION	ELEMENT	HYDROGEN	BORON	BORON	URANIUM
Z	NUMBER OF PROTONS	1	5	5	92
A-Z	NUMBER OF NEUTRONS	0	5	6	146
A	MASS NUMBER	1	10	11	238
Z	ATOMIC NUMBER	1	5	5	92
	SYMBOL	H^1	$_5B^{10}$	$_5B^{11}$	$_{92}U^{238}$

[redacted]

[redacted]

1324

HW-18700

[redacted]

DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

DECLASSIFIED

TA [redacted] 2

MASS NUMBERS AND ABUNDANCE OF ISOTOPES OCCURRING IN NATURE

ATOMIC NUMBER, Z	ELEMENT	SYM.	MASS NUMBER, A (PERCENT ABUNDANCE)	ATOMIC WEIGHT
0	Neutron	n	1(- - -)	
1	Hydrogen	H	1(~100), 2(0.016)	1.0080
2	Helium	He	3(0.00013), 4(~100)	4.003
3	Lithium	Li	6(7.35), 7(92.6)	6.940
4	Beryllium	Be	9(100)	9.013
5	Boron	B	10(18.8), 11(81.2)	10.82
6	Carbon	C	12(98.9), 13(1.1)	12.01
7	Nitrogen	N	14(99.6), 15(0.38)	14.008
8	Oxygen	O	16(99.76), 17(0.039), 18(0.20)	16.0000
9	Fluorine	F	19(100)	19.00
10	Neon	Ne	20(90.5), 21(0.28), 22(9.21)	20.183
11	Sodium	Na	23(100)	22.997
12	Magnesium	Mg	24(78.6), 25(10.1), 26(11.3)	24.32
13	Aluminum	Al	27(100)	26.97
14	Silicon	Si	28(92.22), 29(4.70), 30(3.08)	28.06
15	Phosphorus	P	31(100)	30.98
16	Sulfur	S	32(95.1), 33(0.74), 34(4.2), 36(0.016)	32.006
17	Chlorine	Cl	35(75.4), 37(24.6)	35.457
18	Argon	A	36(0.35), 38(0.08), 40(99.6)	39.944
19	Potassium	K	39(93.2), 40(0.011), 41(6.8)	39.096
20	Calcium	Ca	40(96.9), 42(0.64), 43(0.14), 44(21), 46(0.0032), 48(0.18)	40.08
21	Scandium	Sc	45(100)	45.10
22	Titanium	Ti	46(8.0), 47(7.8), 48(73.4), 49(5.5), 50(5.3)	47.90
23	Vanadium	V	51(100)	50.95
24	Chromium	Cr	50(4.4), 52(83.7), 53(9.5), 54(2.4)	52.01
25	Manganese	Mn	55(100)	54.93
26	Iron	Fe	54(5.9), 56(91.6), 57(2.20), 58(0.33)	55.85
27	Cobalt	Co	59(100)	58.94
28	Nickel	Ni	58(67.9), 60(26.2), 61(1.2), 62(3.7), 64(1.0)	58.69
29	Copper	Cu	63(69.0), 65(31.0)	63.54
30	Zinc	Zn	64(48.9), 66(27.8), 67(4.1), 68(18.6), 70(0.63)	65.38
31	Gallium	Ga	69(60.2), 71(39.8)	69.72
32	Germanium	Ge	70(20.6), 72(27.4), 73(7.7), 74(36.6), 76(7.7)	72.60
33	Arsenic	As	75(100)	74.91
34	Selenium	Se	74(0.87), 76(9.0), 77(7.6), 78(23.5), 80(49.8), 82(9.2)	78.96
35	Bromine	Br	79(50.6), 81(49.4)	79.916
36	Krypton	Kr	78(0.34), 80(2.23), 82(11.5), 83(11.5), 84(57.0), 86(17.4)	83.7
37	Rubidium	Rb	85(72.8), 87(27.2)	85.48
38	Strontium	Sr	84(0.55), 86(9.8), 87(7.0), 88(82.7)	87.63
39	Yttrium	Y	89(100)	88.92
40	Zirconium	Zr	90(51.5), 91(11.2), 92(17.1), 94(17.4) 96(2.80)	91.22
41	Niobium	Nb	93(100)	92.91
42	Molybdenum	Mo	92(15.7), 94(9.3), 95(15.7), 96(16.5), 97(9.5), 98(23.9), 100(9.5)	95.95
43	Technetium	Tc		(99)
44	Ruthenium	Ru	96(5.7), 98(2.22), 99(12.8), 100(12.7), 101(17.0), 102(31.3), 104(18.3)	101.7
45	Rhodium	Rh	103(100)	102.91

(continued on ne[redacted]

1328

HW-18700

[redacted] DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

DECLASSIFIED [redacted]

[redacted]

Table XXVI-2, continued

ATOMIC NUMBER, Z	ELEMENT	SYM.	MASS NUMBER, A (PERCENT ABUNDANCE)	ATOMIC WEIGHT
46	Palladium	Pd	102(0.8), 104(9.3), 105(22.6), 106(27.1), 108(26.7), 110(13.5)	106.7
47	Silver	Ag	107(51.4) 109(48.6)	107.88
48	Cadmium	Cd	106(1.22), 108(0.92), 110(12.4), 111(12.8), 112(24.0), 113(12.3), 114(28.8), 116(7.6)	112.41
49	Indium	In	113(4.2), 115(95.8)	114.76
50	Tin	Sn	112(0.95), 114(0.65), 115(0.34), 116(14.2), 117(7.6), 118(24.0), 119(8.6), 120(33.0), 122(4.7), 124(6.0)	118.70
51	Antimony	Sb	121(57.2), 123(42.8)	121.76
52	Tellurium	Te	120(0.091), 122(2.5), 123(0.88), 124(4.6), 125(7.0), 126(18.7), 128(31.8), 130(34.4)	127.61
53	Iodine	I	127(100)	126.92
54	Xenon	Xe	124(0.094), 126(0.088), 128(1.92), 129(26.24), 130(4.05), 131(21.2), 132(26.93), 134(10.52), 136(8.93)	131.3
55	Cesium	Cs	133(100)	132.91
56	Barium	Ba	130(0.101), 132(0.097), 134(2.42), 135(6.6), 136(7.8), 137(11.3), 138(71.7)	137.36
57	Lanthanum	La	138(0.089), 139(99.9)	138.92
58	Cerium	Ce	136(0.19), 138(0.26), 140(88.47), 142(11.08)	140.13
59	Praseodymium	Pr	141(100)	140.92
60	Neodymium	Nd	142(27.1), 143(12.2), 144(23.9), 145(8.3), 146(17.2), 148(5.7), 150(5.6)	144.27
61	Promethium	Pm		(147)
62	Samarium	Sm	144(3.1), 147(15.0), 148(11.2), 149(13.8), 150(7.4), 152(26.8), 154(22.7)	150.43
63	Europium	Eu	151(47.8), 153(52.2)	152.0
64	Gadolinium	Gd	152(0.20), 154(2.15), 155(14.8), 156(20.6), 157(15.7), 158(24.8), 160(21.8)	156.9
65	Terbium	Tb	159(100)	159.2
66	Dysprosium	Dy	156(0.052), 158(0.090), 160(2.29), 161(18.9), 162(25.5), 163(25.0), 164(28.2)	162.46
67	Holmium	Ho	165(100)	164.94
68	Erbium	Er	162(0.136), 164(1.56), 166(33.4), 167(22.9), 168(27.1), 170(14.9)	167.2
69	Thulium	Tm	169(100)	169.4
70	Ytterbium	Yb	168(0.140), 170(3.03), 171(14.3), 172(21.9), 173(16.2), 174(31.8), 176(12.6)	173.04
71	Lutetium	Lu	175(97.4), 176(2.60)	174.99
72	Hafnium	Hf	174(0.18), 176(5.2), 177(18.4), 178(27.1), 179(13.8), 180(35.3)	178.6
73	Tantalum	Ta	181(100)	180.88
74	Wolfram	W	180(0.14), 182(26.2), 183(14.3), 184(30.7), 186(28.7)	183.92
75	Rhenium	Re	185(37.1), 187(62.9)	186.31
76	Osmium	Os	184(0.018), 186(1.58), 187(1.64), 188(13.3), 189(16.1), 190(26.4), 192(41.0)	190.2
77	Iridium	Ir	191(38.5), 193(61.5)	193.1
78	Platinum	Pt	190(0.012), 192(0.78), 194(32.8), 195(33.7), 196(25.4), 198(7.2)	195.23
79	Gold	Au	197(100)	197.2
80	Mercury	Hg	196(0.155), 198(10.1), 199(17.0), 200(23.2), 201(13.2), 202(29.6), 204(6.7)	200.61
81	Thallium	Tl	203(29.5), 205(70.5)	204.39
82	Lead	Pb	204(1.3), 206(26), 207(21), 208(52)	207.21
83	Bismuth	Bi	209(100)	209.00
84	Polonium	Po		210
85	Astatine	At		(211)
86	Radon	Rn		222
87	Francium	Fr		(224)
88	Radium	Ra		226.05
89	Actinium	Ac		227
90	Thorium	Th	232(100)	232.12
91	Protactinium	Pa		231
92	Uranium	U	234(0.0057), 235(0.71), 238(99.28)	238.07

[redacted]

1230

HW-18700

[redacted]

DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

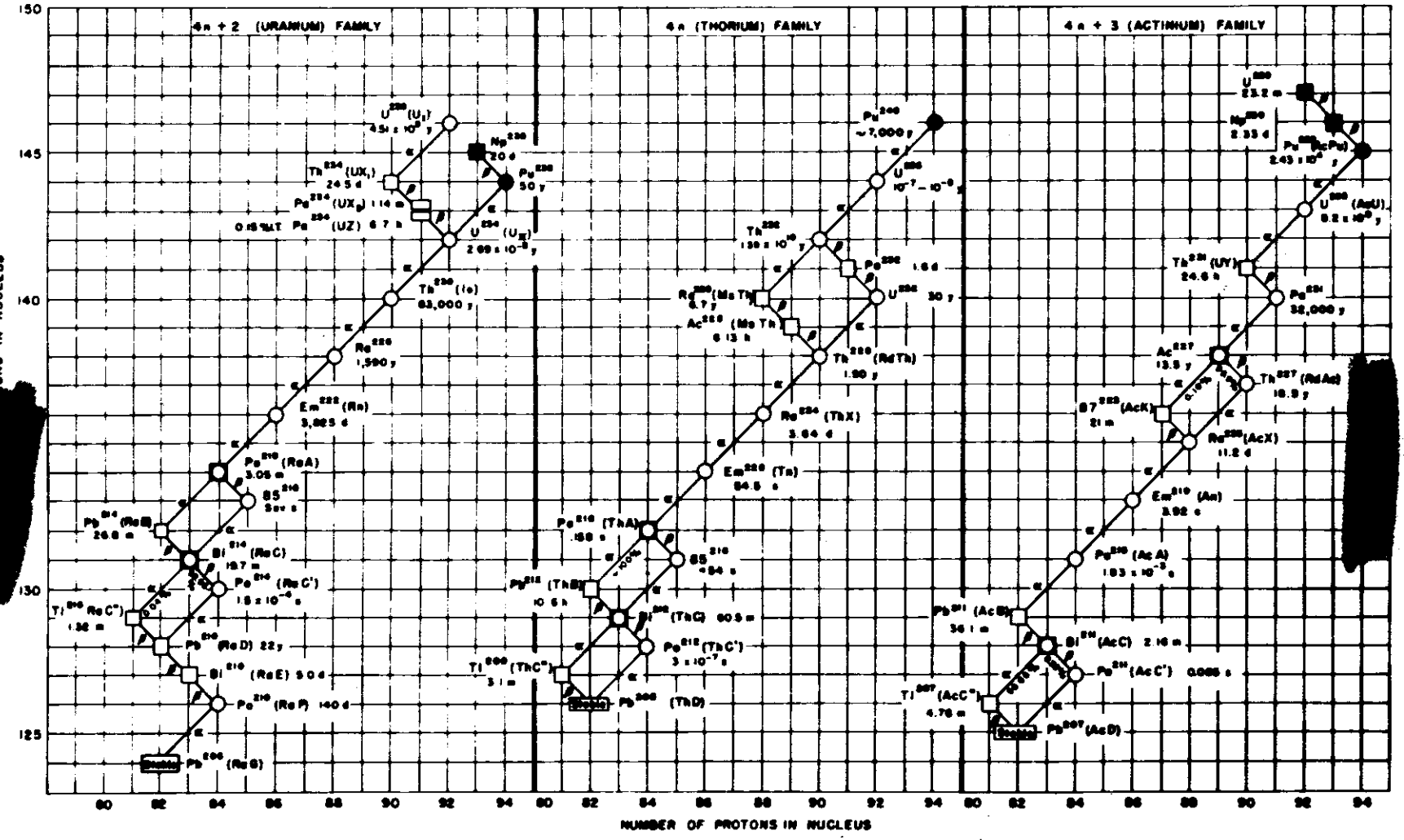
[redacted]

DECLASSIFIED

FIGURE XXVI-3

THE THREE SERIES OF NATURAL RADIOACTIVITIES

INCLUDING RELATED ISOTOPES ARTIFICIALLY PRODUCED



In the above scheme, an alpha disintegration is shown by the symbol α; and beta decay by the symbol β. The following abbreviations are used for denoting half-life values of the radio-isotopes: s – seconds, m – minutes, h – hours, d – days, and y – years. An isomeric transition is indicated by the abbreviation I.T. The classical or historical symbol for each radio-isotope is given in parenthesis as well as the modern designation, using the element symbol and mass number.

● Designates an artificially produced alpha ray emitter.

■ Designates an artificially produced beta ray emitter.

1232

HW-18700

[redacted]

DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

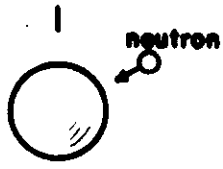
DECLASSIFIED

[redacted]

FIGURE XXVI-4

FISSION OF URANIUM

Liquid Drop Model



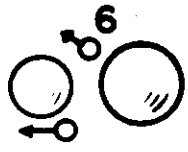
Uranium nucleus in normal spherical shape captures a neutron.

The energy imparted to the nucleus appears as motion of the entire droplet (nucleus).

Violent oscillations may draw the droplet (nucleus) into a dumb-bell shape.

Variations in oscillations result in unequal distribution of mass. Electrical repulsion acts to push ends farther apart.

Fracture occurs resulting in two fission fragments.



The fragments attempt to acquire stability by emission of neutrons.

1234

thn-1870

DECLASSIFIED

[redacted]

THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

DECLASSIFIED

[redacted]

DECLASSIFIED

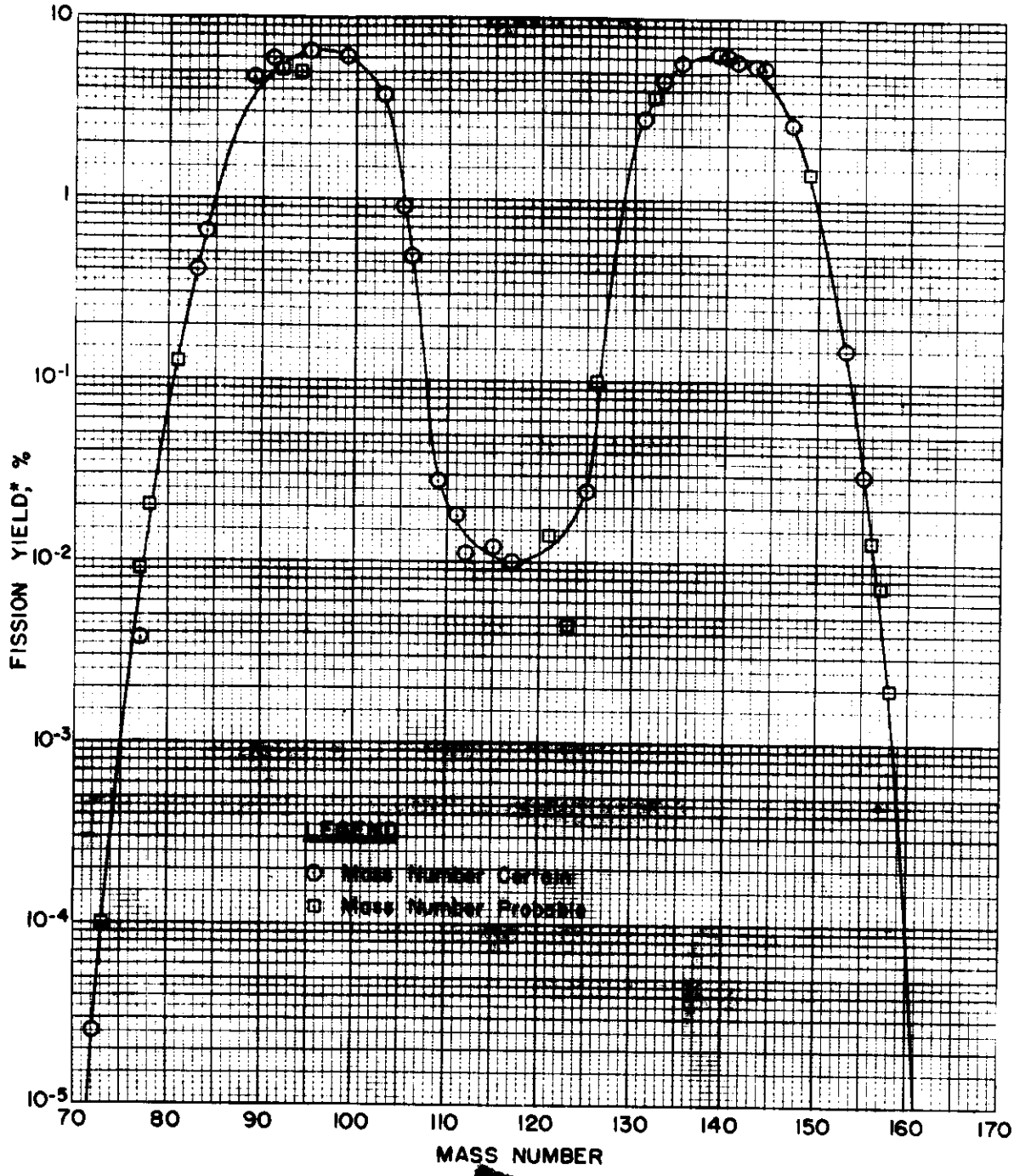
1235

HW-18700

Figure XXVI-5

U[redacted]D CURVE

Source of Data: J. Am. Chem. Soc., 68, 2411, (1946)



*Fission yield is the probability of the occurrence [redacted] a given mass number as the result of fission. Thus a 5.6% yield of fission fragments with [redacted] cates that for every 100 atoms of U^{235} which fission, 5.6 fragments of mass number 135 will occur.

DECLASSIFIED

[redacted]

1334

HW-18700

[redacted]

DECLASSIFIED

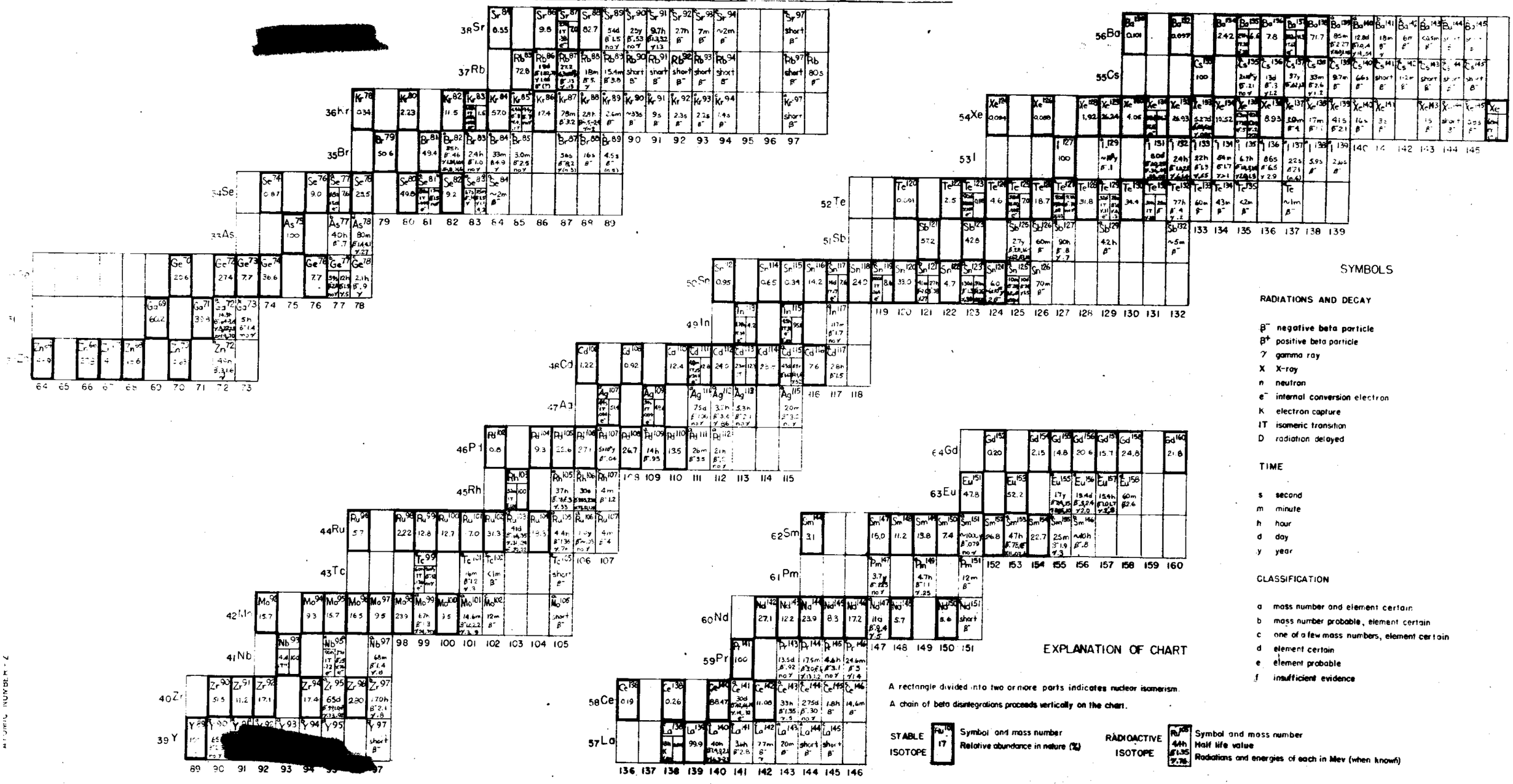
THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

DECLASSIFIED

FIGURE XXVI-6

A CHART OF THE RADIO-ISOTOPES PRODUCED IN PILE FISSION



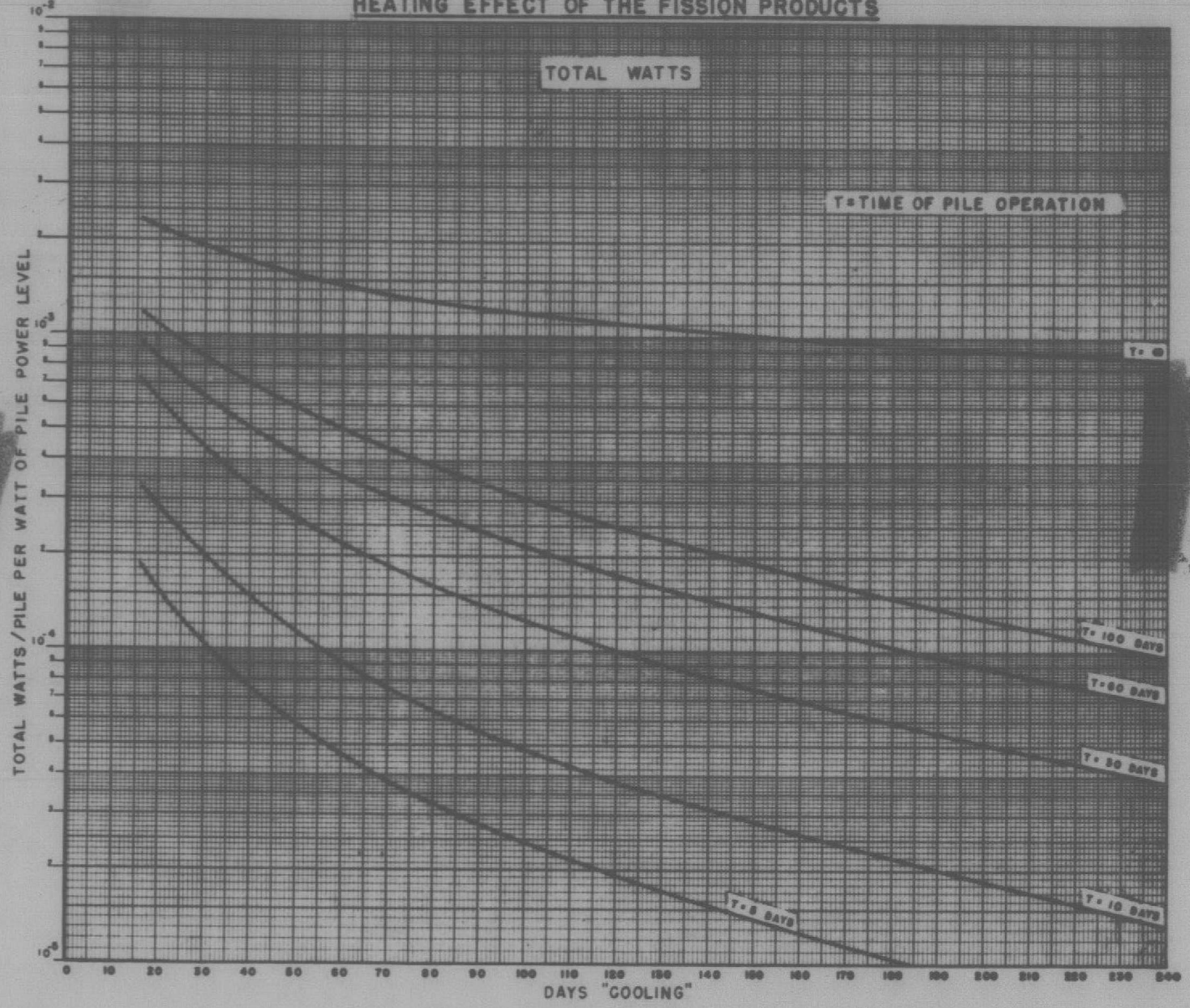
[redacted]

THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

FIGURE XXVI-7

HEATING EFFECT OF THE FISSION PRODUCTS



1340

HW-18700

[redacted]

THIS PAGE
INTENTIONALLY
LEFT BLANK

[redacted]

[redacted]

FIGURE XXVI-8

HEATING EFFECT OF THE FISSION PRODUCTS

[redacted]

HW-18700
FIGURE XXVI-8

1321

1242

HW-18400

DECLASSIFIED

[redacted]

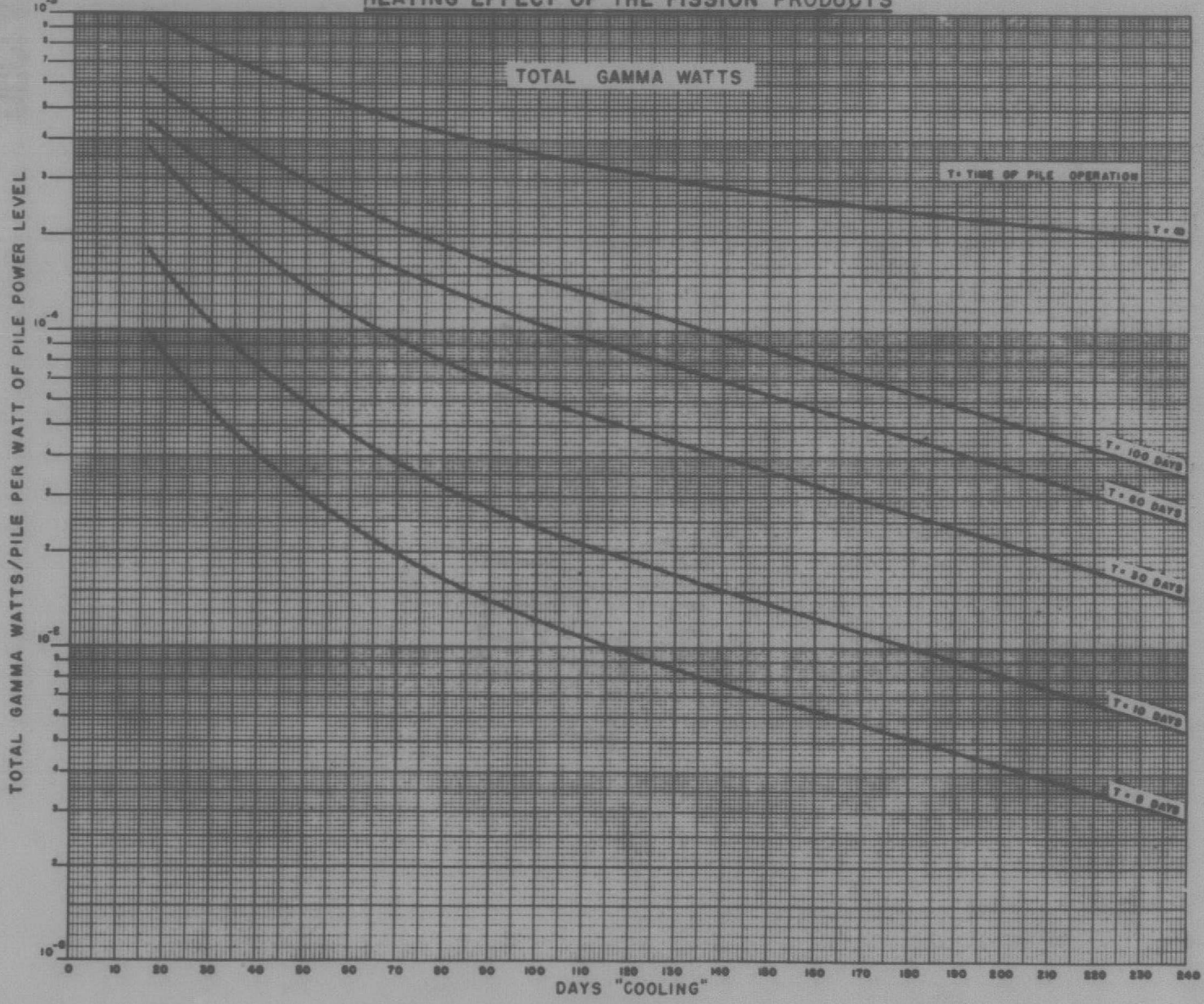
THIS PAGE
INTENTIONALLY
LEFT BLANK

DECLASSIFIED

[redacted]

FIGURE XXVI-9

HEATING EFFECT OF THE FISSION PRODUCTS



HW-18700
FIGURE XXVI-9

1343

1344

HW-18700

[redacted]

DECLASSIFIED

THIS PAGE
INTENTIONALLY
LEFT BLANK

DECLASSIFIED

[redacted]

INDEX

[redacted]

[redacted]

[redacted]

[redacted]

1263

[redacted]

[redacted]

THIS PAGE
INTENTIONALLY
LEFT BLANK